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EFFECTS OF DIURNAL TEMPERATURE DYNAMICS ON CURING OF COLD-EMULSION RECLAIMED ASPHALT PAVEMENTS

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ABSTRACT

Strength development in Cold-Emulsion Reclaimed Asphalt Pavements is gradual and largely dependent on the rate at which curing proceeds. Its early life strength is therefore low and presents a major challenge in material specification for mechanistic pavement design. The solution has been to subject a sample of the mixture to be used in the pavement to accelerated laboratory curing to the attainment of Equilibrium Moisture Content (EMC) condition. Fatigue and Stiffness parameters of the mix along with the chemical properties of the binder can be determined from the cured samples and results incorporated into the pavement design process. The emphasis is in the choice of a laboratory curing protocol that adequately simulates expected curing trends in the field. Protocols in popular use employ steady state curing temperatures to predict long term behaviour of Reclaimed Asphalt Pavements. This project set out to investigate the likely effects of seasonal variations and diurnal cycles in ambient temperatures on the engineering properties of Reclaimed Asphalt and the incorporated binders. To simulate the above phenomena, a predictive model was adopted in computation of high and low temperature peaks that can be expected in two pavements, one in the tropics and the other in a temperate region. The resulting sets of temperatures were used to cyclically cure Reclaimed Asphalt Pavement cores that were manufactured by artificially aging Dense Bitumen Macadam (DBM) in the laboratory and mixing it with a cationic bitumen emulsion. Another set of cores were subjected to steady temperatures as is the current practice. This acted as a control for the two cyclic temperatures under study. Use was made of a suite of tests available in the Nottingham Asphalt Tester (NAT) to determine stiffness and fatigue properties of the mix under the three treatments. Bitumen binders recovered at the end of curing was tested for penetration, softening point temperatures and percentage of Asphaltenes. The findings pointed at a likelihood of severe treatment of asphalt samples by the existing laboratory curing protocols. Curing at a steady temperature led to a lower fatigue life, over estimation of early life strength and underestimation of long term strength of the cold asphalt. Low penetration values, high softening point temperatures and high percentages of Asphaltenes in bitumen from the cured samples attest to severe aging of the samples.

Keywords: cold-recycling, accelerated curing, cyclic temperatures, reclaimed asphalt pavement, in-situ conditions.

1. INTRODUCTION

Pavement recycling as a means of rehabilitating distressed rigid and flexible pavements has continued to grow in popularity due to the environmental and economic benefits it brings. Materials from the two major types of pavements can successfully be recycled, although recycling of flexible pavements dominates. This is due to its popular use in paved areas. To reliably popularize pavement recycling as an alternative to conventional rehabilitation techniques, the performance capabilities of recycled materials should be easy to characterize and specify.

Pavement recycling falls into the categories of Hot Recycling (HR) and Cold Recycling (CR). Hot recycling uses the same technology as Hot Mixed Asphalt and therefore has the disadvantage of huge energy consumption and associated high gaseous emissions. Cold recycling, on the other hand, utilizes softer grades of bitumen, bitumen cut-backs, foamed bitumen or bitumen emulsions. Foamed bitumen and bitumen emulsions have gained favour owing to their good Health Safety and Environment (HSE) record [1].

Whereas it has an excellent environmental record, Cold-Emulsion Reclaimed Asphalt Pavement has a low early-life strength which has resigned its use to low volume roads and works in remote areas where strength is not a key requirement. This, however, has not lessened the popularity of emulsion-reclaimed asphalt pavements. They stand out in addressing reflection cracking, which is a major form of distress suffered by pavements with stiff bases.

Curing is the phenomenon that controls the rate of strength gain in Cold-Emulsion Reclaimed Asphalt Pavements. The role of curing is twofold. One is to rid the mix of moisture so as to allow for direct contact between aggregates and the binder and the second is, to activate the aged binder in Reclaimed Asphalt Pavements via the process of ‘fluxing’.

The project set out to study the effects of alternate heating and cooling resulting from seasonal and diurnal pavement temperature cycles on the rate of curing, strength development and fatigue properties of Cold-Emulsion Reclaimed Asphalt mixtures. The aim was to assess the suitability of the existing protocols in mimicking on-site conditions without exaggerating the aging process in bitumen.

2. REVIEW OF LITERATURE

2.1 Trends in pavement recycling

Use of pavement recycling as an alternative to the conventional pavement rehabilitation methods started on a small scale in the 1930's and gained much of its popularity in the 1970's due to the energy crisis that hit the globe in 1973 [2]. The resulting fuel associated rise in construction costs spark a research interest into viability of pavement recycling starting in Europe, Australia, United States and South Africa. Laboratory models and field trial sections were constructed and monitored over time to ascertain the engineering properties of the recycled asphalts and to devise ways of improving their performance to match those of conventional rehabilitation materials.

2.2 Curing protocols

Researches by individuals and agencies have adopted a number of accelerated laboratory curing protocols in an attempt to estimate service life of cold mixes. All protocols encountered in the course of this study use steady state temperatures and a few are cited hereunder.

- 3 days cure at 60°C corresponding to the construction period and early field life of the mix, i.e. up to 1 year in the field. [3]
- 14 days cure at 35°C and Relative Humidity of 20% corresponding to between 1 and 3 years in the field in the temperate regions and under low to medium traffic volumes [4, 5, 6]
- 14 days at 18°C at Relative Humidity of 50% to simulate short term curing (a few weeks after laying) in temperate region. [5]
- Curing in the mould for 24 hours at ambient temperatures followed by 48 hours curing at 40°C to simulate 6 months in the field [7]

Two cyclic temperature protocols were developed by adopting pavement temperature models that have hitherto found use in specification of performance grade bitumen and in determination of pavement stiffness parameters for back-calculations in Falling Weigh Deflection (FWD) tests [8]. Asphalt pavements are subjected to cycles of heating and cooling in response to seasonal temperature variations and diurnal temperature cycles. A combination of factors such as solar radiation, air temperature, pavement reflectance, precipitation, freezing-thawing cycles alongside other physical and environmental conditions act to influence the temperature dynamics in the pavement.

Superpave (Superior Performing Asphalt Pavements) under the Strategic Highway Research Program (SHRP) developed a simple algorithm for computation of asphalt pavement temperatures at various depths below the asphalt surface [9]. The model uses ambient temperatures and latitude data to compute pavement temperatures at the surface and depths below the surface, at any point in the globe. For the purpose of this study, two temperature peaks for two cities, one in the tropics and the other in the temperate environment, were computed using the maximum and minimum air temperature using equations (1) and (2) below. The driest and warmest periods were chosen as being the appropriate for laying asphalt concrete in both cities. That falls between June and October in Nairobi and the period between Mid-May and Mid-August in London.

$$T_{Surf} = T_{Air} - 0.00618Lat^2 + 0.2289Lat + 24.4 \text{ ------------ } (1)$$

Where,

T_{Surf} = Temperature at the surface (°C)

T_{Air} = Ambient Temperature (°C)

Lat = Latitude of the region concerned (Degrees)

For temperatures at different depths, the relationship below is used.

$$T_d = T_{Surf} (1 - 0.063d + 0.007d^2 - 0.004d^3) \text{ ---------------- } (2)$$

Where,

T_d = Temperature at depth d (°F)

T_{Surf} = Temperature at the surface (°F)

d = Depth from the surface (inches)

Fatani *et al* [10] conducted a study on pavement temperatures in Saudi Arabia and found out that the maximum temperatures in flexible pavements are recorded at depths of 20mm below the pavement surface. That is approximately halfway through a typical pavement surfacing and can logically represent the average conditions in the pavement.

Climatic data obtained from *BBC Weather* were used to compute the average minimum and maximum air temperature as well as the number of sunshine hours [11, 12]. The resulting values of the upper and lower temperature peaks for the tropical and temperate regions were 44°C and 34°C and 37°C and 29°C respectively. The protocol proposed by Asphalt Institute i.e., 14 days at 35°C [4] was adopted as the steady state curing temperature. Three thermostatically controlled conditioning cabinets were used to apply the chosen curing temperatures in the laboratory.

Table-1. Minimum and maximum pavement temperatures.

Location	Latitude (Degrees) [13]	T_{Air}		$T_{Surface}$				T_{20mm}			
		Min	Max	Min: °C/°F		Max: °C/°F		Min: °F/°C		Max: °F/°C	
Nairobi	1.27	11.6	22.2	36.3	97.3	46.9	116.4	92.9	33.8	111.1	43.9
London	51.5	11.8	20	31.6	88.8	39.8	103.6	84.8	29.3	98.9	37.2

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3. MATERIALS, EQUIPMENT AND METHODS

3.1 Materials

The research utilized 60 asphalt cores of average dimensions 100mm diameter and 50mm height manufactured in the laboratory using aged Dense Bitumen Macadam of granite origin, dust, mineral filler and a cationic bitumen emulsion. The focus was on cold emulsion reclaimed asphalt pavement fit for use as surfacing and thus aggregates of maximum size 20mm were used.

Aggregates

The aggregates used in this research were derived from artificially aged Dense Bitumen Macadam (DBM) obtained from Cliffe Hill Quarry in Leicester. Dust and the Filler were also obtained from the same source. The residual binder in the DBM after being kept at ambient temperature for close to a month was determined as 4.25% by mass of aggregates. Its penetration ranged between 20dmm and 21dmm. To simulate aging, the DBM was reheated to 160°C, laid in slabs of dimensions 305mm by 305mm by 50mm and allowed to cool for two days before being crushed and tested for residual bitumen. The penetration of bitumen had dropped to 14 dmm signifying substantial aging.

Bituminous binder

A cationic emulsion containing 60% bitumen and 40% water was used as the binder in the preparation of the cold mix. The bitumen emulsion of Venezuela origin was supplied by Nynas Asphalts, UK. At the time of supply, the supplier reported the penetration of the emulsion as being 48dmm and its softening point as 51.4°C. The bitumen emulsion constituted 6% by mass of dry aggregates. Pre-wetting water constituting 1.5% by mass of dry aggregates was incorporated to disperse the emulsion besides improving the workability.

3.2 Equipment

To monitor performance parameters of the three sets of specimens as curing proceeded, use was made of a suite of tests available in the Nottingham Asphalt Tester (NAT) [14]. NAT was the main piece of equipment but other equipment that came in handy in preparation and conditioning of samples included a Jaw Crusher, Sieve Shaker, Hobart Mixer, Shear Gyratory Compactors and Conditioning Cabinets.

Shear Gyratory Compactor was used to manufacture test cores in the laboratory by simulating the kneading action of rollers used to compact asphalt on site.

3.3 Mix design and specimen preparation

Reclaimed Asphalt Pavement, Dust and Filler were graded separately and blended in proportions of 65%, 30% and 5% respectively to produce an overall gradation falling within the envelope defined by the lower and upper bounds of the Overseas Road Notes No. 19 and 31 [15, 16]. Several proportions were tried with the aim of approaching the maximum dry density curve as defined by Cooper Equation below [17].

$$P = \frac{(100-F)(d^n - 0.075^n)}{D^n - 0.075^n} + F \quad (3)$$

Where,

P = Percent material passing sieve size d (mm)
D = Maximum aggregate size (mm)
F = Percent filler (%)
n = Exponent that defines the curvature of the gradation curve, usually 0.45 for maximum packing of particles [18].

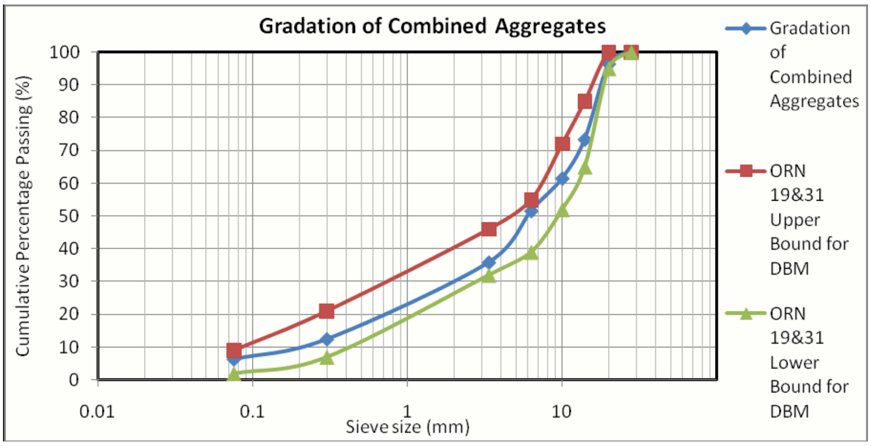

Figure-1. Aggregate gradation.

Cylindrical specimens for laboratory curing and testing were prepared based on the determined mixed aggregates gradation, emulsion requirement and the optimum pre-wetting water content. The target dimensions for both the ITFT and ITSM tests were 100mm diameter and 50mm height. The aggregates were batched into metallic cans and conditioned overnight in a conditioning cabinet set at 35°C to drive out any moisture.

The aggregates were then mixed in a Hobart mixer with addition of 1.5% water and 6% bitumen emulsion by mass of dry aggregates. The resultant mix was then weighed into steel moulds and compacted in the

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gyratory compactor to the target density. The cylinders were cured at room temperature for 24 hours before being transferred into the respective thermostatically controlled conditioning cabinets where weight loss was tracked as a means of evaluating curing progression.

3.4 Testing methods

Indirect tensile stiffness modulus test (ITSM)

Stiffness of an asphalt mix is a reflection of its ability to effectively spread tyre loads to the underlying pavement layers without damaging the foundations.

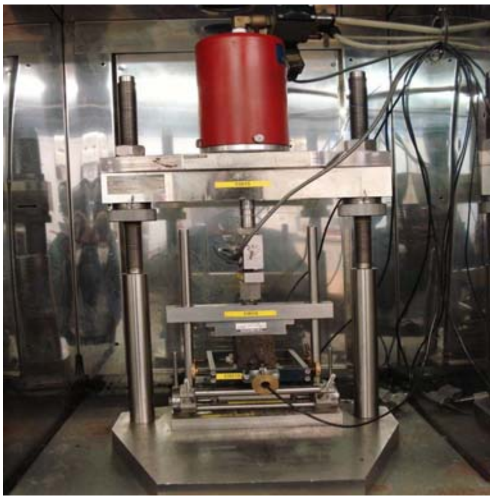

Figure-2. NAT in the ITSM configuration.

Stiffness tests in the laboratory can be performed either by the Uniaxial Test, Indirect Tensile Test or the Beam Tests. In this exercise, stiffness test was done in accordance with BS DD 213: 1993, which specifies the method of performing Indirect Tensile Stiffness Modulus Test in the Nottingham Asphalt Tester

Indirect tensile fatigue test (ITFT)

Fatigue is the structural damage suffered by a material when subjected to a cyclic or repeated stress that is generally of magnitude below the ultimate tensile strength of the material. Traffic and thermal loads in a pavement induce alternate stretching and relaxation in the binder matrix which eventually leads to fracture being manifested as fatigue cracks on the road surface.

Determination of fatigue life in the laboratory can be done using simple flexure, uniaxial test or the indirect tensile test. The latter is preferred due to ease in specimen fabrication and is the method adopted in the draft specification - BS DD ABF: 2003 and used in this exercise.

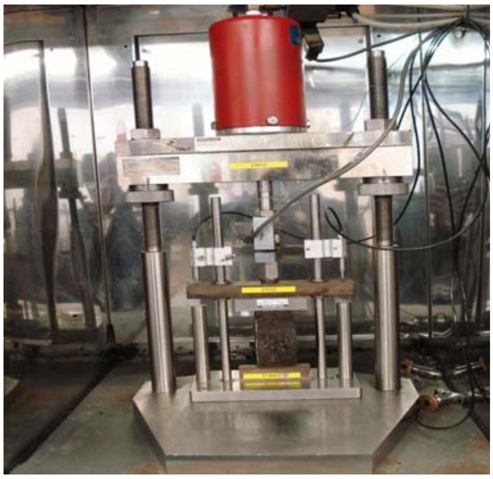

Figure-3. NAT in the ITFT configuration.

4. RESULTS AND DISCUSSIONS

4.1 Moisture loss

Moisture loss with time was reckoned from the residual moisture as a percentage of the total mix by mass. Curiously, the three curing regimes displayed closely similar trends in water loss. As can be seen from Figure-4 below, the three protocols followed more less the same trend in moisture loss. 10% of the total water content was lost in the 24 hour period of curing in the mould and another 80% was lost after curing for one day in the condition cabinets. 90% of the total moisture content had been lost on the second day, suggesting that temperature may not be the key player in the evaporation mechanism. Equilibrium Moisture Content (EMC) seemed to have been achieved after 6 days of curing.

4.2 Indirect tensile stiffness modulus test (ITSM)

Stiffness modulus of cylinders from the three curing protocols was determined at six time intervals. The cyclic temperatures started on the lower peaks and the effect was reflected in the stiffness modulus determined after a day of curing in the ovens. That would have been equivalent to on-site laying of cold-emulsion in the evening when the temperatures are low.

Strength development in the cylinders cured at 35°C rose gradually in an almost linear manner while those under cyclic temperatures rose gradually with decreasing gradients towards a peak.

Wide variations in material properties are common in cold mixes but a general trend can be drawn from the results plotted in Figure-5 above. It can be deduced that laboratory curing of cold emulsion asphalts at 35°C closely predicts the intermediate strength, overestimates the early strength and underestimates the long term strength. The tropical conditions show a faster rate of strength development which may generally be underestimated if use is made of the existing protocol of curing at 35°C. A stiffness modulus of 2000 Mpa is sufficient to support low to medium traffic [17], which, in

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this case, can be achieved from as early as 12 days in the tropical conditions.

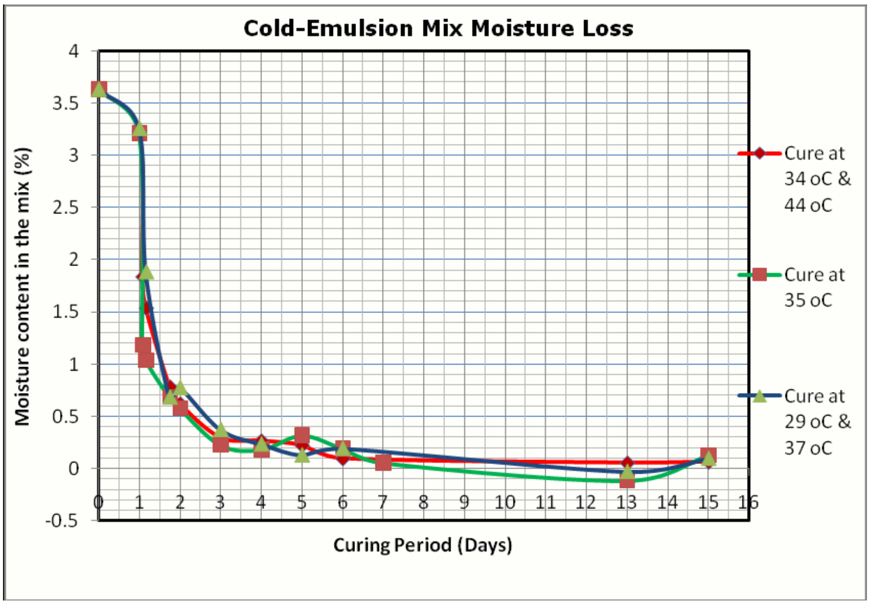

Figure-4. Cold-Emulsion RAP moisture loss.

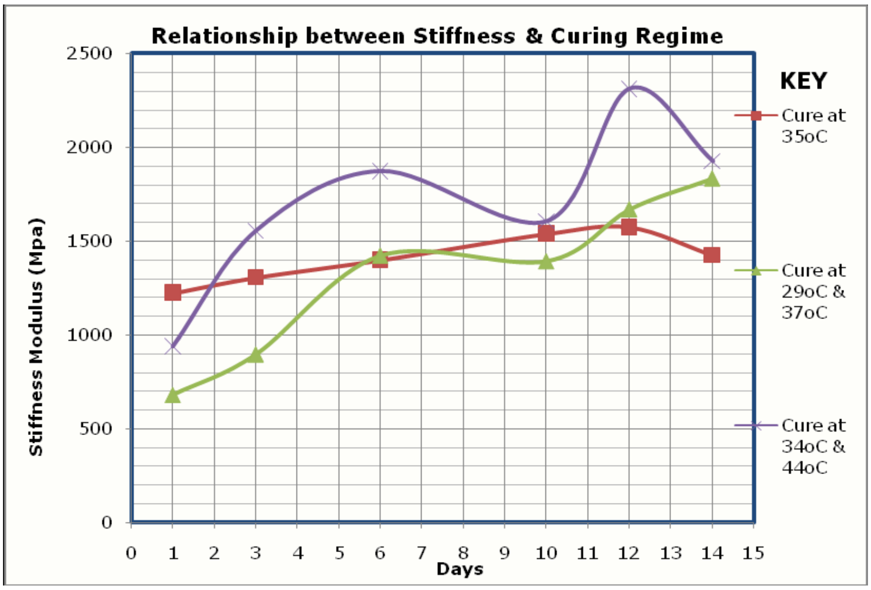

Figure-5. Strength evolution in cold-emulsion RAP.

4.3 Indirect tensile fatigue test (ITFT)

The aim of the test is to load the specimen to failure by applying alternate stress or strain, and to determine the number of load applications to cause the failure. Cylinders cured for 10 and 12 days were curing for a further four and two days respectively. This was aimed at providing additional number samples for determination of fatigue life which was targeted at samples cured for 14 days. Ten samples conditioned overnight were subjected to load pulses ranging from 600 kPa to 100 kPa.

Fatigue characteristics are determined by plotting maximum tensile horizontal strain versus life to failure on logarithmic scales. Fatigue characteristics of materials cured under the three regimes were compared by plotting the maximum horizontal tensile strains against the number of cycles to failure and generating fatigue relationships by use of power trend lines. Fatigue life of each mixture was obtained from its linear regression model by assuming logarithmic linearity of fatigue life. Samples cured cyclically at 29°C and 37°C exhibited the highest level of fatigue resistance while those cured at 34°C and 44°C had the lowest life to failure.

Early failure by fatigue cracking in the mix cured cyclically at 34°C and 44°C can be explained by considering the likely effects of high temperatures on the bitumen binder. At temperatures of 44°C, bitumen could be losing the volatile components and thus ending up being brittle.

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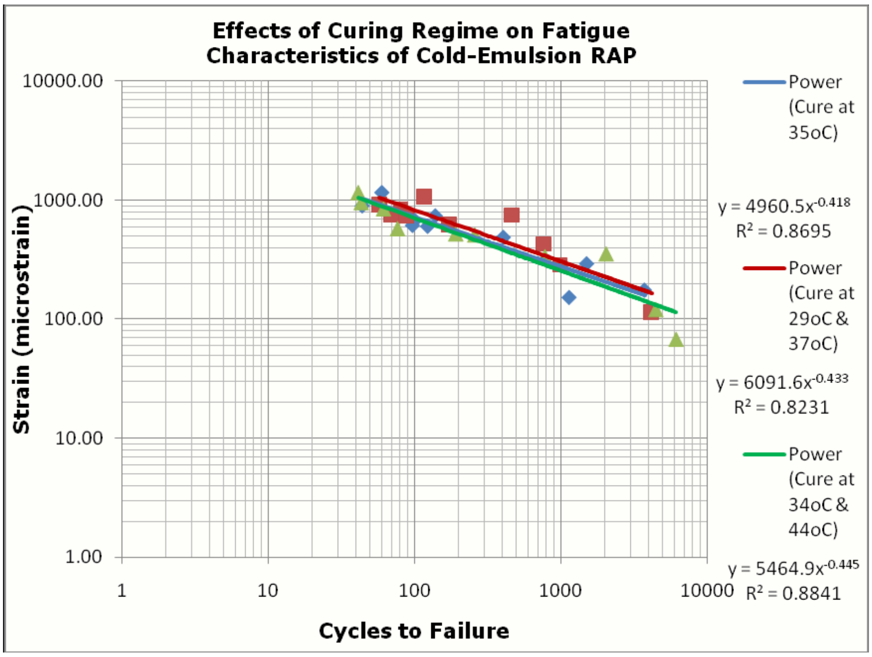

Figure-6. Comparison of fatigue life.

Table-2. Linear regression values.

Curing protocol	Equation based on N_f	N_f at 100με	R^2
35°C	$y = 4960.5x^{-.418}$	11,384	0.87
29°C and 37°C	$y = 6091.6x^{-.433}$	13,237	0.82
34°C and 44°C	$y = 5464.9x^{-.445}$	8,026	0.88

4.4 Properties of recovered binders

Bitumen was recovered from the cores before and after being subjected to the three curing conditions. Table-3 below presents the characterization of the binders in terms of Penetration, Softening Point and percentage of Asphaltenes. These three parameters were used to assess severity of aging of bitumen caused by the curing regimes. The results indicate that curing at the steady temperature of 35°C results in the highest degree of aging as compared to the other two regimes. The increase in Asphaltene contents after curing is partly due to activation of bitumen in the Reclaimed Asphalt Pavement.

It is therefore logical to suggest that curing at the steady temperature of 35°C to simulate on site conditions may be too harsh a treatment for cold-emulsion Reclaimed Asphalt Pavement used in both the temperate and tropical conditions.

Table-3. Properties of recovered binders.

		Penetration (dmm)	**Softening point** (°C)	**Asphaltene content** (%)
Before curing		26	61	14.8
After curing	35°C	21	64	16.3
	29°C and 37°C	32	59.2	16.2
	34°C and 44°C	22	63	16.1

5. CONCLUSION AND RECOMMENDATIONS

The study of the fundamental properties of the materials cured under three curing protocols, two cyclic and one steady state, revealed a potentially useful correlation between laboratory curing temperatures and on-site curing. The results from the study form a basis for a detailed study into the precise behaviour of cold asphalts under different site conditions. Based on the results of the laboratory tests, the study makes the following tentative conclusions.

- Prevailing pavement temperature has a greater effect on the rate of 'fluxing' or activation of aged binder in a Cold-Emulsion Reclaimed Asphalt Pavement than it has on the rate of moisture loss.

- Steady temperature laboratory curing regimes severely age the binder in the Cold-Emulsion Reclaimed Asphalt Pavement mixtures.

Recommendations

The study gives an indication of the behaviour of Cold-Emulsion RAP though extensive monitoring of actual field performance still needs to be done to validate the results. A study incorporating more variables that interactively influence the curing process needs to be conducted. The study makes the following recommendations for future research:

- Laboratory generated cores should be introduced in one go into the conditioning cabinets to prevent absorption of moisture by the already cured samples.
- Effects of humidity and air draught be incorporated in laboratory curing to give a better simulation of the on-site conditions.
- Cyclic temperatures in the laboratory should be applied stepwise to better simulate the diurnal temperature cycles.

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